

BACKWARD COLLINEAR ACOUSTO-OPTIC INTERACTIONS IN BULK MATERIALS

by

J.E.B. Oliveira and C.K. Jen*

CTA-ITA-IEEC
12225 SAO JOSE DOS CAMPOS
SAO PAULO, BRAZIL

* Industrial Materials Research Institute,
National Research Council of Canada,
Boucherville, Quebec J4B 6Y4

ABSTRACT

Theoretical studies of backward collinear acousto-optic interactions (BCAOI) in both isotropic and anisotropic materials are presented. Such interactions have become of practical interest as the result of recent progress on very high frequency piezoelectric transducers. BCAOI configurations which involve longitudinal acoustic waves in fused silica, germanium and several uniaxial single crystals are analyzed. The acoustic propagation loss at high frequency in these materials are discussed.

1. INTRODUCTION

Acousto-optic interactions in both isotropic and anisotropic materials have been reported by many researchers [1-5]. These interactions can take place when the wavevectors of optical and acoustic waves are either collinear or noncollinear. In isotropic materials interactions in which the incident optical waves and acoustic waves are collinear and propagate in the same direction are forbidden whereas in anisotropic materials such interactions are allowed provided that the incident and diffracted optical waves have different polarizations. Those configurations in which the wavevectors are collinear and the optical waves propagate in opposite directions are, here, called backward collinear acousto-optic interaction (BCAOI). BCAOI can take place in either isotropic or anisotropic crystals. As a result of the recent advent of efficient high frequency piezoelectric transducers [6,7] BCAOI has become very attractive for devices applications. Furthermore BCAOI can also exist in a fiber waveguide [8]. In this paper several aspects of BCAOI in both isotropic and anisotropic bulk materials are investigated.

In a BCAOI an acoustic wave with wavevector k_a and frequency f_a interacts with an incident optical wave with wavevector k_{oi} and frequency Ω_{oi} and gives rise to an optical wave with wavevector k_{od} and frequency Ω_{od} as illustrated in Figure 1. In such interactions conservations of wave-vector (momentum) and frequency (energy) leads to the following relationships

$$K_a - K_{oi} = K_{od} \quad (1)$$

and

$$\Omega_{oi} - f_a = \Omega_{od} \quad (2)$$

respectively. K 's represent the magnitude of the corresponding wavevectors k 's. Equation (1) can be satisfied in practical devices because of the advent of the efficient high frequency piezoelectric transducers (e.g. > 10 GHz) [6,7], which allow k_a values to be higher than that of the optical wavevector k_{oi} . So far only high frequency longitudinal transducers have been reported experimentally, however in theory high frequency shear transducers may be obtainable [9].

In order to evaluate the diffraction efficiency of BCAOI let us consider the geometry shown in Fig.2; both the incident optical waves and acoustic waves propagate along the Z axis. Using the formulation presented in Ref.[10] it can be shown that the ratio between the intensities of the diffracted (I_d) and incident (I_i) optical waves is given by the following expression,

$$\frac{I_d}{I_i} = \eta \frac{\sin^2 [\eta + (\Delta K L/2)]^{1/2}}{\eta + (\Delta K L/2)^2} \quad (3)$$

where

$$= \frac{\pi^2}{2 \lambda_o^2} M \left(\frac{P_a}{WH} \right) L^2 \quad (4)$$

$$M = \frac{n_i^3 n_d^3}{\rho v_a^3} (p_{eff})^2 \quad (5)$$

n_i, n_d : refractive index of the incident and diffracted waves

ρ : material density

p_{eff} : effective photoelastic constant

P_a : acoustic power

v_a : acoustic wave phase velocity

W : acoustic transducer width

H : acoustic transducer height

λ_o : optical wavelength in vacuum

L : collinear interaction length

ΔK : phase mismatching factor ($\Delta K = K_a - K_{oi} - K_{od}$)

M : acousto-optic figure of merit

In this paper the objective is to use equations (1) to (3) to emphasize several merits of BCAOI in isotropic and anisotropic materials. Section 2 discusses the acousto-optic figure of merit in a few isotropic and anisotropic materials. The analysis of acoustic propagation losses at high frequencies is given in section 3. Conclusions and discussions are outlined in Section 4.

2. ACOUSO-OPTIC FIGURE OF MERIT

A few common materials employed in acousto-optic interactions such as fused silica, germanium (Ge), lithium niobate (LiNbO_3), quartz, tellurium dioxide (TeO_2) and tellurium (Te) are used for illustrative calculations. Some of the relevant characteristics of these materials are given in Table 1 [11].

2.1 Isotropic Materials

Fused silica and germanium are chosen due to that fused silica is a well known low loss isotropic material both optically and acoustically, and germanium which is optically isotropic but acoustically anisotropic exhibits very low optical loss at $10.6 \mu\text{m}$ CO_2 laser wavelength. Longer optical wavelength means that the acoustic frequency required for BCAOI is lower, thus less acoustic attenuation. Since only longitudinal waves have been demonstrated at very high frequency, therefore BCAOI which involves this type of acoustic waves is considered here. The arbitrarily chosen propagation direction of the longitudinal acoustic waves is along [100] axis of the Ge single crystal. For BCAOI in isotropic materials there is no rotation of the polarization of the optical waves throughout the interaction length.

Assuming that in the geometry illustrated in Fig.2 the incident optical waves are linearly polarized with electric field lying in the xy plane the effective photoelastic constant for a BCAOI which involves longitudinal acoustic waves in optically isotropic materials is

$$p_{\text{eff}} = p_{12} \quad (6)$$

From Ref.[11] one obtains $p_{12} = 0.27$ for fused silica at $0.6328 \mu\text{m}$ while for germanium at $10.6 \mu\text{m}$ $p_{12} = 0.235$. Using the longitudinal acoustic velocity given in Table 1 and expression (5) the following figures of merit are obtained:

$$M = 15.24 \cdot 10^{-16} \frac{\text{S}}{\text{kg}} \quad \text{for fused silica at } 0.6328 \mu\text{m} \quad (7a)$$

$$M = 3.53 \cdot 10^{-13} \frac{3}{g} \left(\frac{S}{k} \right) \text{ for Ge} \quad \text{at } 10.6 \mu\text{m} \quad (7b)$$

It is noted that such high figures of merit make BCAOI very attractive from the point of view of acoustic power level required to obtain a certain diffraction efficiency. Moreover BCAOI exhibits the feature that the phase mismatching factor, ΔK , is to ,first order, not sensitive to small change of the orientation of optical waves and hence it is of interest for implementing acousto-optic tunable filters.

For the above two materials the acoustic frequency and the optical wavelength shifts predicted by Eqns. (1) and (2) were calculated. Results are presented in Table 2. This Table also includes uniaxial crystals which are considered below.

2.2 Uniaxial crystals

Four uniaxial single crystals listed in Tables 1 and 2 are considered as substrates for BCAOI. Two types of configurations are considered namely, (i) those in which the optical and acoustic wavevectors are orthogonal to the optical axis and (ii) configurations in which both wavevectors lie in a plane which is arbitrarily oriented with respect to the optical axis. The wavevector diagram for the former configuration is shown in Fig.3. Such configuration exhibits a wide angular aperature irrespective of the crystal being positive or negative uniaxial crystals.

Using Eqn.(1) one obtains the following acoustic frequencies at the phase matching condition, $\Delta K = 0$,

$$f = \frac{v_a}{\lambda_o} (n_e + n_o) \quad \text{when the incident and diffracted waves have different polarization} \quad (8a)$$

$$f = \frac{v_a}{\lambda_o} 2n_o \quad \text{when both waves are ordinary} \quad (8b)$$

$$f = \frac{v_a}{\lambda_o} 2n_e \quad \text{when both waves are extraordinary} \quad (8c)$$

For illustration purposes only figures of merit of BCAOI in lithium niobate single crystal are calculated. The results are given in Table 3. Again only longitudinal acoustic waves are considered and propagate along the [100] direction of lithium niobate with phase velocity $v_L = 6570$ m/s.

Another configuration of interest is that when the optical axis is off-set from the interaction plane, the optical wavevector loci for the ordinary and extraordinary polarized waves are no longer concentric as illustrated in Fig.4 [10]. The "gap" between the loci allows us to implement a BCAOI involving, for instance, an ordinary wave which is coupled into an extraordinary wave. The required frequency for such interactions as a function of θ , the offset angle, is given by

$$f_a = \frac{v_a}{\lambda_o} \left[\frac{n_e}{(n_o^2 \cos^2 \theta + n_e^2 \sin^2 \theta)^{1/2}} + 1 \right] \quad (9)$$

and that for an ordinary to an ordinary BCAOI is given by Eqn.(8b). By subtracting Eqn.(8b) from Eqn.(9) one obtains

$$f_a = \frac{v_a n_o}{\lambda_o} \left[\frac{n_e}{(n_o^2 \cos^2 \theta + n_e^2 \sin^2 \theta)^{1/2}} - 1 \right] \quad (10)$$

By properly choosing "O" one can make f_a small enough to fall within the acoustic transducer bandwidth. It means that the diffracted light may be controlled to have ordinary or extraordinary polarizations by changing the acoustic frequency.

3. CONSIDERATIONS OF ACOUSTIC PROPAGATION LOSS

The collinear acousto-optic interaction strength is in general proportional to the interaction length normalized by the acoustic wavelength $\lambda_a (= v_a / f_a)$. Since the acoustic attenuation normally increases as a function of f_a^2 , therefore the interaction strength deteriorates as the acoustic frequency increases.

Table 1 lists the material properties of some common materials for acousto-optic interactions [11]. n is the optical refractive index, whereas subscripts o and e denote the ordinary and extraordinary waves respectively. Under the condition of k_a equal to $2k_o$, the corresponding acoustic frequency, acoustic propagation distance, loss and time delay across a length of 100 acoustic (longitudinal wave) wavelengths in these materials for optical ordinary waves only are given in Table 2. It means that in Table 2, k_o is equal to $2\pi n_o / \lambda_o$. Optical wavelength $1.31 \mu\text{m}$ is chosen because it is currently used in single mode optical fiber telecommunications. Since Ge and Te are optical transparent around CO_2 laser wavelength but not the other materials listed in Table 1, $10.6 \mu\text{m}$ is selected for Ge and Te only. Since the frequency

shifting is performed at such high frequencies, the shift in optical wavelength is also of interest and therefore listed in Table 2 as well. It can be seen that the loss may be tolerable for some of the practical acousto-optical device applications. The one-way tuned loss for a multilayer zinc oxide thin film transducer on a sapphire substrate has been reported to be 17 dB at around 12 GHz and room temperature [6]. This transducer loss may be improved further [6,7,8].

4. CONCLUSIONS

Theoretical analysis of backward collinear acousto-optic interaction (BCAOI) in bulk materials was presented. Fused silica, germanium and several uniaxial single crystals were used as examples for the analysis. The acousto-optic figure of merit were presented for longitudinal acoustic waves only. The merits of BCAOI can be summerized as below:

- A. There is no "forbidden" interaction direction in any isotropic, uniaxial or biaxial material having low acoustic and optical loss.
- B. Incident light with ordinary or extra-ordinary polarization may be coupled into diffracted light with ordinary, extraordinary or both polarizations by proper choices of crystal orientations. This provides a few interesting applications. For instance, by taking advantage of these different polarizations, frequency multiplexed acoustic waves ($f_{a1}, f_{a2}, \dots$) may be used to modulate the wavelength division multiplexed optical waves ($\Omega_{oi1}, \Omega_{oi2}, \dots$), silmultaneously.
- C. By a proper choice of crystal orientations there may exist a

very small gap between the loci of the ordinary and the extraordinary optical waves. It means that within the bandwidth of the acoustic transducer the diffracted light can be controlled to have ordinary or extra-ordinary polarizations by changing the acoustic frequency. In general this particular direction also has very large optical aperture. One possible application is that there may exist a direction that the coupling strength to the ordinary and the extraordinary are equal. This property may be used as a beam splitter with an output having orthogonal polarizations.

ACKNOWLEDGEMENT

This work was partially supported by the Natural Science and Engineering Research Council of Canada.

REFERENCES

- [1] Harris, S.E. and Wallace, R.W., 'Acousto-optic tunable filter', J. Opt. Soc. Am., 1969, 59, pp.774-747
- [2] Nieh, S.T.K. and Harris, S.E.: 'Aperture-bandwidth characteristics of the acousto-optic filter', J. Opt. Soc. Am., 1972, 62, pp.672-676
- [3] Dixon, R.W.: 'Acoustic diffraction of light in anisotropic media', IEEE J. Quantum Electron., 1967, QE-3, pp.85-93
- [4] Chang, I.C.: 'Acoustooptic devices and applications', IEEE Trans. Sonics and Ultrason., 1976, SU-23, pp.2-22
- [5] Houston, J.B., Gottlieb, M., Yao, S.K., Chang, I.C., Tracy, J., Smithline, L.M. and Wolga, G.J.: 'The potential for acousto-optics in Instrumentation: an overview for the 1980's', Opt. Eng., 1981, 20, pp.712-718
- [6] Hadimioglu, B., Khuri-Yakub, B.T., Goddard, L.C. and Quate, C.F.: 'Multi-layer ZnO acoustic transducers', Proc. IEEE Ultrasonics Symp., 1986, pp.361-364
- [7] Hadimioglu, B., La Comb, Jr., L.J., Wright, D.R., Khuri-Yakub, B.T. and Quate, C.F.: 'High efficiency, multiple layer ZnO acoustic transducers at millimeter wave frequencies', Appl. Phys. Lett., 1987, 50, pp.1642-1644
- [8] Jen, C.K. and Goto, N.: 'Backward collinear guided-wave-acousto-optic interactions in single mode fibers', to be published.
- [9] Akcakaya, E., Adler, E.L. and Farnell, G.W.: "Anisotropic superlattice transducers: characteristics and models", to be presented in Ultrasonics Symp. Chicago, Ill. Oct.3-5, 1988.
- [10] For example, Oliveira, J.E.B.: 'Generalized anisotropic acousto-optic diffraction in uniaxial crystals', Ph.D Dissertation, Dept. of Elect. Engg. McGill University, 1986.
- [11] Data were collected from many references but mainly from: Uchida, N. and Niizeki, N.: "Acoustooptic deflection materials and techniques", Proc. IEEE, 1973, 61, 1073-1092

Table 1 ACOUSTIC AND OPTICAL PROPERTIES OF SEVERAL MATERIALS [11]

Material	V (m/s) L	Acoust. Atten. (db/cm-GHz ²)	n _o	n _e
Fused Silica	5933	12	1.458	1.458
Ge [1 0 0]	4924	30	4.00	4.00
LiNbO ₃ [1 0 0]	6572	0.15	2.300	2.208
Quartz [0 0 1]	6354	2.1	1.544	1.553
TeO ₂ [0 0 1]	3049	15.0	2.2585	2.4112
Te [1 0 0]	2318	60	4.7939	6.2433

Table 2 ACOUSTIC PROPERTIES AT $k_a = 2 k_o$

MATERIAL	ACOUST. FREQ. (GHz) at λ_a	DISTANCE $100 \lambda_a$ (μ m)	ATTEN. $100 \lambda_a$ (db)	TRANSIT TIME $100 \lambda_a$ (ns)	WAVELENGTH SHIFT (A°)
Fused Silica	13.21 (1.31 μ m)	44.9	9.41	7.57	0.76
Ge [1 0 0]	3.72 (10.6 μ m)	132.5	5.50	26.91	13.92
LiNbO ₃ [1 0 0]	23.08 (1.31 μ m)	28.5	0.23	4.33	1.32
Quartz [0 0 1]	14.98 (1.31 μ m)	42.4	2.00	6.68	0.86
TeO ₂ [0 0 1]	10.51 (1.31 μ m)	29.0	4.81	9.51	0.60
Te [1 0 0]	2.10 (10.6 μ m)	110.5	2.92	47.69	7.85

Table 3 BCAOI FIGURES OF MERIT IN LITHIUM NIOBATE

INTERACTION	$M \times 10^{-16} \frac{3}{g} (S/k)$
ord. to extraord.	17.29
ord. to ord.	8.06
extraord. to extraord.	31.89

FIGURE CAPTIONS

Fig.1 BCAOI

Fig.2 BCAOI configuration with acoustic transducer

Fig.3 BCAOI in positive uniaxial crystals whose optical and acoustic wavevectors are orthogonal to the optical axis. For negative crystals n_e and n_o are interchanged.

Fig.4 BCAOI in positive uniaxial crystals whose optical and acoustic wavevectors lie in a plane which is arbitrarily oriented with respect to the optical axis.

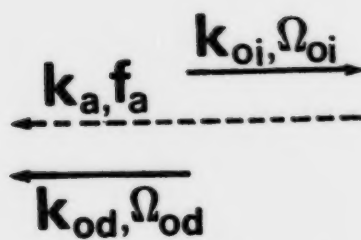


Fig. 1

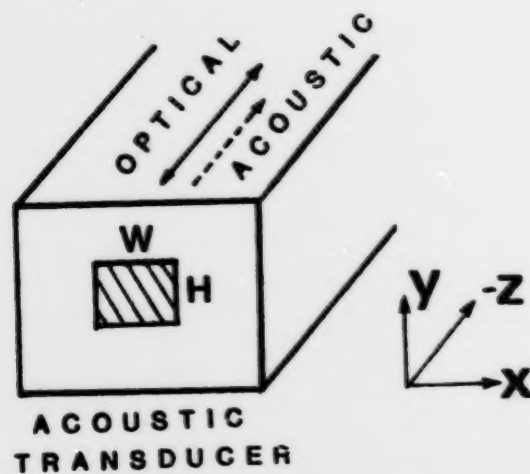


Fig. 2

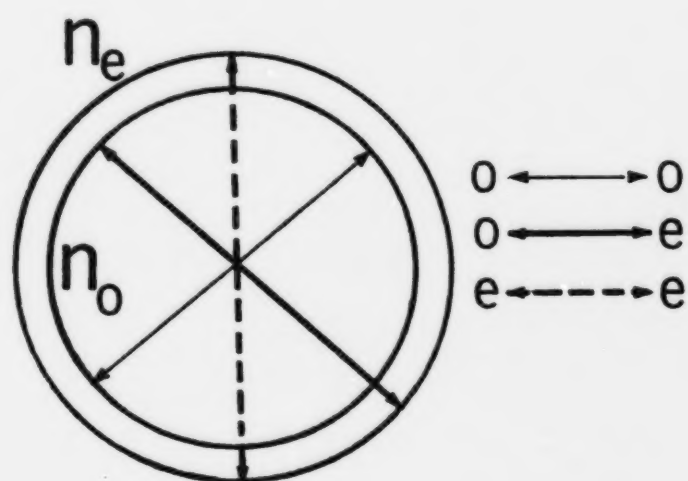


Fig. 3

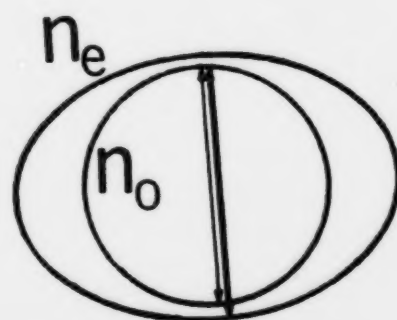


Fig. 4